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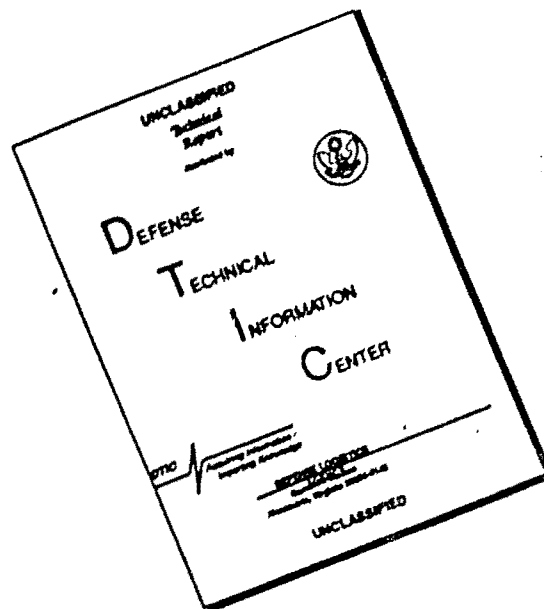
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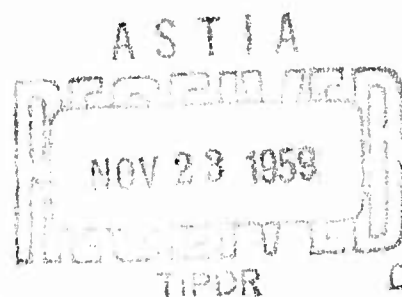
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Barometric Devices and Fuze Design (U)

Irvin Pollin

15 October 1959

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DA-5N06-01-001
ORD Proj. TN3-9101
DOFL Proj. 90101


15 October 1959

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BAROMETRIC DEVICES AND FUZE DESIGN (U)

Irvin Pollin

FOR THE COMMANDER:
Approved by


Don I. Mittleman
Chief, Mathematical Consultants



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CONTENTS

	Page No.
ABSTRACT	5
1. INTRODUCTION	5
2. GENERAL THEORY	6
3. LOCATION AND DESCRIPTION OF PRESSURE ORIFICES	8
4. LABORATORY AND FLIGHT EVALUATION OF BAROMETRIC DEVICES	11
4.1 Fixed-Angle Nose Probe	12
4.2 Free-Swiveling-Vane Nose Probe	16
4.3 Body-Trailing Probe	17
4.4 Use of Orifices Located on the Surface Contour of a Vehicle	18
4.5 Use of Barometric Devices at High Supersonic and Hypersonic Speeds	21
5. THE BARO-SWITCH ELEMENT	22
6. WIND-TUNNEL AND LABORATORY SIMULATION OF FLIGHT CON- DITIONS	24
7. METEOROLOGIC EFFECTS ON ALTITUDE DETERMINATION	27
8. SUMMARY	28
REFERENCES	31
SUPPLEMENTAL BIBLIOGRAPHY	32

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ABSTRACT (U)

The general theory, operation and design of several existing barometric devices are reviewed. The devices are designed to operate a switch upon attaining a preset pressure. Some of the problems that confront the designer of a barometric fuze system are presented. Evaluation of the accuracy of a fuze system is given by means of an examination of the individual parameters which affect its operation. In addition, an extensive bibliography is included to aid the fuze designer or the user of barometric devices to pursue special problems.

1. INTRODUCTION

The purpose of this paper is to present the general theory and operation of a barometric fuze system and to show results by referring to the systems used on specific missiles. From the general theory it can be seen that the various factors that influence the atmospheric-pressure determination may be individually considered. By this means, it is possible to understand some of the difficulties that arise in the design of a barometric system. In addition, the sensitivity of the system to meteorologic variations is discussed.

Although the work has general application to barometric devices, particular emphasis will be placed on barometric fuze systems for which a single precise altitude determination is desired, for altitudes ranging between sea level and 100,000 ft, and for vehicle speeds up to 5000 fps. Even within these limitations, it will be seen that the design of a barometric system varies with different missiles. A most important conclusion of this presentation is that the design of a precision barometric system must include consideration of the performance of the instrument and vehicle in flight.

A review of the general theory and operation of a barometric fuze system is given in section 2. The action of the constituent components and the various factors which influence the fuze performance are explained. The effect of the motion of a vehicle on the pressure field that is to be measured is described in section 3. This disturbance of the pressure field largely influences the type of probe that may be used to sense the atmospheric pressure. Consequently, a discussion of the various forms of pressure-sensing elements that are used is presented in section 4 along with some discussion of the parameters that influence their performance. The results of flight-test and wind-tunnel experimental data for specific barometric devices are presented. In section 5, the operation of several designs of a pressure transducer and plumbing connecting the pressure-sensing element are described.

In section 6, the wind-tunnel simulation of flight conditions and other laboratory tests used in the research and development of a barometric-fuze system design are described along with an evaluation of the application of these laboratory procedures. In addition to the instrumentation accuracy, the system is sensitive to meteorologic variations. A discussion of meteorologic variations is given in section 7. Finally, the above work is summarized and an extensive bibliography is provided which will enable the fuze designer or user of barometric devices to study the subject in greater detail or pursue special problems.

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2. GENERAL THEORY

A barometric device consists essentially of an orifice exposed in some manner to the atmosphere which is joined by tubing to instrumentation calibrated to determine the atmospheric pressure. The barometric devices considered herein are those in which a vehicle carries the device through the atmosphere at various speeds and altitudes. The purpose of the device is to indicate altitude or to perform some function (such as close a switch) upon attaining a preset altitude, where the altitude is related to the atmospheric pressure through the hydrostatic-pressure equation or a predicted altitude-pressure relation. Ideally, the motion of the pressure-sensing element through the atmosphere causes no disturbance of the fluid and thereby has no effect on the atmospheric pressure; ideally, the calibrating instrumentation is instantaneous and completely accurate. The accuracy in the predicted altitude-pressure relation is, of course, independent of the accuracy of the barometer. In addition, the response of the system must be essentially independent of the dynamics of the vehicle (such as changes in speed or in the angle of incidence between the vehicle axis and flight path), the mechanical vibration generated by aerodynamic forces and transmitted through the vehicle structure, the aerodynamic heating of the vehicle and pressure-sensing element, etc.

The above effects on the performance of a barometric-fuze system as well as others will be described in the succeeding sections. Although these effects are extremely important, they do not alter the fundamental operation of a barometric system. Consequently, the present description will be limited to pressure-sensing systems subject to known transient pressures.

The transient behavior of a gas pressure-sensing system is described in ref 1.* The assumptions in the theory are that the dead time (ratio of the length of tube to the speed of sound) due to transportation lag in the transmission of a pressure signal may be neglected and the volume ratio (the ratio of the tube to reservoir volume) is small. As a result of these two assumptions, the volume flow may be considered uniform along the tube length and disturbances occur simultaneously throughout the system with varying magnitudes. Such a system is called a lumped-constant system.

Assuming small adiabatic pressure changes, the relation between the reservoir and orifice pressures given by the lumped-constant system reduces to a second-order differential equation with constant coefficients. These coefficients and hence the principal design characteristics, the undamped natural frequency and damping ratio, are functions only of the tube length, tube diameter and the reservoir volume. The equations given for the undamped natural frequency, ω_0 , and damping ratio ζ are as follows:

$$\omega_0 = \sqrt{\pi r^2 \gamma g R g T_0 / LV} \quad \text{and}$$

$$\zeta = (4\mu/p_0 r^3) \sqrt{VLgRgT_0/\pi \gamma}, \quad \text{where}$$

*References are listed in the bibliography.

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r = radius of tube, ft

L = length of tube, ft

V = volume of reservoir, ft³

γ = ratio of specific heats, dimensionless

g = acceleration of gravity, ft/sec²

R_g = gas constant, ft-lb/(lb) (°F)

T_0 = initial steady-state absolute temperature, °R

p_0 = initial steady-state absolute pressure, lb/ft²

μ = absolute viscosity, lb-sec/ft²

The change in the reservoir pressure of a system, p_c , due to a pressure disturbance, p_d , depends on the value of the damping ratio in the manner shown by the following equations:

Case I (Underdamped) $0 \leq \zeta < 1$

$$\frac{p_c}{p_d} = 1 - \frac{e^{-\zeta \omega_0 t}}{\sqrt{1 - \zeta^2}} \cos \left(\sqrt{1 - \zeta^2} \omega_0 t - \tan^{-1} \frac{\zeta}{\sqrt{1 - \zeta^2}} \right)$$

Case II (Critically damped) $\zeta = 1$

$$\frac{p_c}{p_d} = 1 - e^{-\omega_0 t} - \omega_0 t e^{-\omega_0 t}$$

Case III (Overdamped) $\zeta > 1$

$$\frac{p_c}{p_d} = 1 - e^{-\zeta \omega_0 t} \left[\frac{\zeta}{\sqrt{\zeta^2 - 1}} \sinh \sqrt{\zeta^2 - 1} \omega_0 t + \cosh \sqrt{\zeta^2 - 1} \omega_0 t \right]$$

As can be seen from these equations, the response of a given system varies with the operating pressure and temperature (initial pressure and temperature of the transient) and with the pressure transient, p_d .

Excellent agreement is shown in ref 1 between the experimental and theoretical responses of a system, where, using an initial pressure of 29.32 in. mercury absolute, initial temperature of 525°R, tube radius of 0.0215 in., tube length of 16.75 in., reservoir volume of 0.202 in.³, the system was shown to require about 0.012 sec to attain the steady-state condition following a 1-in. mercury step-pressure disturbance.

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Pressure measurements made in flight on the NACA RM-10 research test vehicle at various altitudes for Mach numbers ranging between 0.9 and 3.3 are described in ref 2. The time-lag constant for the pressure system is stated as less than 0.0007 so that the corresponding time-lag to measure 99 percent of the pressure transient is 0.003 sec. Consequently, the lag error in the pressure determination is insignificant.

A more sophisticated theory of a gas pressure-sensing system that treats tube end corrections, heat transfer within the tube and transmission-lag corrections for a large range of frequencies of oscillation is given in ref 3. The lumped-constant system would appear to give adequate results when the selection of the tube and reservoir dimensions is in agreement with the assumptions noted previously. Otherwise, reference should be made to the theory presented in ref 3 in order to observe the significance of some of the effects omitted in the lumped-constant system.

3. LOCATION AND DESCRIPTION OF PRESSURE ORIFICES

The sensing element used in the measurement of atmospheric pressure consists of a single orifice or sometimes several orifices mounted flush in the walls of the body of the vehicle or on a specially designed tube, called a probe, attached to some part of the vehicle. In order that the pressure at the orifice have a value equal to the true atmospheric pressure, it is necessary to measure the static pressure and thereby eliminate the component of the impact pressure caused by the motion of the body. Consequently, when it is feasible to do so, the orifice axis is installed normal to the flight path. The pressure at the orifice is then a direct measure of the atmospheric pressure. Orifices with axes not normal to the flight path may also be used in which case the orifice pressure is some function of the true atmospheric pressure.

The problem of measuring atmospheric pressure is complicated by the fact that a body in motion tends to disturb the enveloping flow field and thereby alters the ambient pressure at the body surface. This is true for almost all body shapes and speeds. Accordingly, the measurement of static pressures or pressures on the body contour may result in large errors in the determination of the atmospheric pressure. Consequently, it is necessary to locate the orifices either where the pressure disturbance is negligible or is a known quantity.

At subsonic speeds, the pressure disturbances due to the motion of a body completely envelop it, appearing in front of the body as well as in its wake. The case is similar for transonic speeds, which is generally defined for vehicle speeds between Mach numbers 0.8 and 1.3. For supersonic and hypersonic motion, the pressure field is generally undisturbed ahead of body but everywhere else the pressure field varies from the undisturbed free-stream value. When the vehicle moves at other than transonic speeds, except for short distances in the wake immediately aft of the body, the disturbed pressures may be considered essentially steady.* (There exist regions on the body which take exception to this statement, such as the region where

*The term "steady" signifies that the quantities involved are not functions of time.

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transition from laminar to turbulent flow occurs.) However, in some instances, as for transonic speeds, the disturbed pressure field near the body may be expected to fluctuate by as much as 10 percent. In addition, the disturbed pressure field for transonic flow is extremely sensitive to small variations in the undisturbed free-stream atmospheric temperature and pressure and to small changes in the body speed.

The extent of the disturbance due to the body motion also depends on the body shape. For large bodies such as a bomb or missile, at any speed, the difference between the undisturbed free-stream pressure and the pressure at a point on the body surface may easily be 25 percent. The significance of this is indicated by meteorologic data which show that for altitudes below 30,000 ft a 1-percent change in the atmospheric pressure corresponds to an altitude variation between 200 and 300 ft (ref 4).

Instead of measuring atmospheric pressure directly, it may be argued that if the pressure disturbance due to the motion of the body is essentially unique and the pressures on the surface of the body differ from the undisturbed pressures in some known manner (at least at one point on the body surface), then a calibration procedure could be adapted to determine atmospheric pressure. Such a technique using one or more orifices mounted on the body surface to measure atmospheric pressure would be possible, by determining in advance the relation between the undisturbed free stream and body pressures, from wind-tunnel and flight tests. The above discussion assumed the body shape was known, but in flight the vehicle does not fly true and the body axis will generally be inclined to the direction of flight. This variation in angle of incidence also affects the body speed. When the body speed changes or the angle of incidence between the body axis and flight path changes slightly, each by an amount that normally occurs during flight, the pressure field at a given point on the body may easily change by several percent.

In addition, the body pressures are influenced by local surface conditions such as the roughness caused by paint, imperfections in the body shape such as small indentations, waves or small ripples, etc -- all of these irregularities being within the usual tolerance of manufacture of the body shape. The extent to which variations in body imperfections and flight conditions influence the surface pressures depends on the shape and speed of the body, flight conditions, the position at which the pressure is being measured, etc. Other factors, such as the temperature of the body surface, aerodynamic heating, etc which influence the boundary layer during flight will alter the pressure distribution on the body surface. Consequently, for a given vehicle, unless all the factors that give rise to the disturbance of the atmospheric pressure can be predicted as they will occur in flight, it appears that large errors in the determination of altitude may result by installing orifices in the walls of the body surface to measure atmospheric pressure. It is beyond the scope of this work to attempt to state numerical values for these effects. However, as will be discussed in section 4, reference may be made to experimental data where wind-tunnel and flight measurements of surface pressures have been reported for bodies of various shapes.

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As will be discussed in section 4, when high precision in the altitude determination is not required, the orifices may be installed directly in the surface of the body, providing wind-tunnel and flight tests show that such locations are where variations in the surface pressure are small when subject to typical variations in flight conditions. Otherwise, to relate accurately the orifice pressure to the undisturbed free-stream value, pressure probes of special design are necessary. These probes are generally mounted forward of the body nose where the pressure disturbance caused by the motion of the body is negligible. In the event the probes cannot be mounted forward of the body, they are located to one side of the body so that errors in the calculated pressure disturbance caused by the body motion will be small. Accordingly, the pressure disturbance at the orifices is due only to the motion of the probe itself which, by virtue of the special probe design, causes little disturbance of the free-stream pressure. Then the problem of accurately measuring atmospheric pressure is essentially reduced to designing a tube for which the effects of flight conditions can be determined with high precision and can be "zeroed" out by some calibration procedure. (The discussion of these probes is given in the next chapter.)

The pressure field for many vehicles and for static-pressure probes may be obtained from theoretical predictions, wind-tunnel and free-flight measurements. These data are obtained as part of the aerodynamic studies to determine the performance of a vehicle and to evaluate pressure-measuring instrumentation. Reference to the literature for similarly shaped bodies will aid in locating the orifices and designing suitable pressure probes. Thus, the error in the atmospheric-pressure determination may often be estimated from previous calibrations of similar installations. The publications of the National Advisory Committee for Aeronautics are a principal reference source which may be consulted for theoretical and experimental information on the pressure distributions of missiles, aircraft, etc and on pressure-measuring instrumentation. Both classified and unclassified indices of new NACA publications are prepared biweekly; in addition, previous work is indexed under subject headings.

Often, conclusions regarding the location of an orifice are based on laboratory models. Laboratory models are generally precision made and the surface condition differs from that of the manufactured item. In addition, they are generally not full-scale models. Consequently, flight tests may show that the variations in the orifice pressure on the manufactured models are not satisfactory. Hence, it cannot be over-emphasized that the final selection of an orifice location must be based on full-scale, flight-tested manufactured models.

The technique for the installation of orifices in a surface is generally independent of the body size, shape, or other characteristic and is often independent of the flight conditions and purpose of the barometric device. Any one of a number of techniques may be used to install the orifices. The following description gives a general idea of the design and procedure for installing orifices in the walls of a body surface or probe.

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Orifices used to determine atmospheric pressure are generally small with an average diameter of 0.01 to 0.02 in. (ref 5). The edge of the opening should be flush with the surface at which the pressure is being measured -- it is important that no protruding burrs or surface roughness appear in the neighborhood of the orifice -- and the axis should be approximately perpendicular to the surface. The following description taken from ref 5 illustrates the procedure of placing orifices in a surface:

"Several soft metal tubes about 0.05 in. internal diameter -- 'compo' tubing -- are let into grooves cut in the surface of the model so that their outer surfaces protrude slightly above that of the model. They are held in place by wax run into the grooves in a molten state, and the whole is then made good by scraping to preserve the designed contours of the model. The tubes are soft and thick-walled, so that there is no difficulty in scraping their slightly projecting exteriors flush with the model surface."

4. LABORATORY AND FLIGHT EVALUATION OF BAROMETRIC DEVICES

The preceding section discussed the disturbance of the pressure field caused by the motion of a vehicle and the consequent difficulty of obtaining pressures at an orifice that could be used to determine atmospheric pressure. It was seen that in order to measure atmospheric pressure, the orifices must either be located at a point on the vehicle where the disturbance of the pressure field is known or installed on a probe of special design. In each case, the orifices are located so that the orifice pressure is a known function of the atmospheric pressure. In addition, with the use of specially designed probes, it is possible to obtain orifice pressures that are identical with atmospheric pressures.

The present section discusses several types of probes which may be mounted on the vehicle and are designed so that the orifice pressure is always identical with the atmospheric pressure. Three such probes are described. In addition, the experimental results for orifice installation in the walls of several vehicles are described. An analysis of the probe designs and wall installations is given and conclusions are derived concerning their accuracy.

Based on theory and experimental data, the accuracy of a pressure-measuring system may be indicated for all altitudes up to at least 100,000 ft and all speeds up to Mach number 10. Reference will be made to the experimental flight data of barometric fuzing systems for both subsonic and supersonic speeds. In addition, flight data at high Mach numbers of pressure sensing systems used in connection with the determination of the performance of research vehicles will be discussed. Generally, barometric fuzing systems are designed to operate at Mach numbers below 3. The data that will be described appear sufficient to indicate the accuracy of a barometric fuzing system for suitably designed probes when the orifices are placed in the undisturbed airstream away from the induced pressure-field disturbance caused by the moving vehicle or when the orifices are located in the base of the vehicle. In addition, the accuracy of specific barometric fuze systems for orifices placed on the surface contour and for orifices otherwise located in flow regions subjected to the influence of the vehicle motion will be indicated.

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4.1 Fixed-Angle Nose Probe

The general shape of a static pressure probe is that of a fine needle. Essentially, the fixed-angle static pressure probe consists of a cylindrical tube of a very small diameter having a conical or ogival nose with apex angles of 10 degrees or less. The distance between the apex of the conical or ogival nose and the orifices is necessarily large to avoid the nose effects on the static pressure. According to wind-tunnel data, the measured values of the static pressure equal the free-stream static pressures and are independent of the axial location of the orifices when the orifices are placed eight or more cylinder diameters aft of the nose-cylinder shoulder and the probe is aligned with the windstream* (ref 6). Assuming perfect instrumentation and alignment with the wind, the value of the static pressure measured in flight is equal to the ambient pressure.

The principal disadvantage in using a fixed-angle probe is that the static pressures are sensitive to the wind direction and vary radially about the probe when the incident wind is not parallel to the probe axis. For other than small angles of incidence, this variation must be taken into account to avoid large errors in the determination of the ambient pressure. Based on theory and experimental observation, even when the flow over the probe is supersonic, the approximation to the radial variation of the static pressure with angle of incidence is about the same as that for two-dimensional incompressible flow over a circular cylinder with zero circulation (ref 6). The reason for the similarity may be seen as follows: For either compressible or incompressible flow, the radial pressure distribution over the probe is essentially a function of the velocity component normal to the cylinder axis and independent of the component parallel to the axis. At small angles of incidence, the cross velocity will be subsonic even when the wind speed is supersonic. For example, the cross velocity is only 348 fps for a wind speed of 4,000 fps at an angle of incidence of 5 degrees. Since the location of the orifices is far removed from the ends of the probe, the crossflow over the orifices is essentially two-dimensional and geometrically similar to that for a two-dimensional circular cylinder. Hence, the usual equation for the radial pressure distribution on a circular cylinder in perfect (i.e., inviscid) incompressible two-dimensional flow may be used as an approximation for the radial pressure distribution at supersonic speeds on a probe at axial locations where a two-dimensional crossflow occurs. Accordingly the approximate radial static pressure distribution for a probe at an angle of incidence with the wind stream is given by the equation:

$$P_m = P + 1/2 \rho V_c^2 (1 - 4 \sin^2 \theta), \quad (1)$$

*For example, one of the probes described in ref 6 has an ogival nose and a cylindrical afterbody. The probe has a cylinder diameter of 0.25 in. and a total length of 8 in.; the ogival nose is 2 in. long and the diameter of the orifices is 0.020 in.

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where P_m is the measured static pressure, P is the true static pressure, $1/2 \rho V_c^2$ is the dynamic pressure for the flow normal to the probe axis, and θ is the radial location on the probe measured from the forward stagnation point* (ref 6, 7).

The above equation is strictly applicable for an inviscid fluid, and since this is not the case for a real fluid, the experimental radial pressure distribution will differ from the theoretical distribution. As is well known, the crossflow Reynolds number** is primarily determinative of the radial pressure distribution (ref 8). For example, the crossflow Reynolds number for a 1/2 in. diameter cylindrical probe at an angle of incidence of 5 degrees, wind speed of 4000 fps and sea-level atmospheric conditions is about 93,000. Since the crossflow Reynolds number decreases with increasing altitude in accordance with the reduction of the ambient density, it may be assumed that the crossflow Reynolds number for a pressure probe will generally be less than 10^5 .

According to the wind-tunnel experimental data examined in ref 8 for Reynolds numbers less than 10^5 , the pressure developed for two-dimensional flow on a circular cylinder from the forward stagnation point to about ± 30 degrees is independent of the Reynolds number and varies in accordance with the above equation. From about ± 30 to ± 180 degrees, the pressure is generally less than the ambient and varies with the crossflow Reynolds number. The experimental data indicate that the minimum radial pressure occurs at about ± 70 degrees from the forward stagnation point instead of ± 90 degrees as indicated by the above equation. Furthermore, separation of the laminar boundary layer takes place between ± 80 degrees and ± 90 degrees from the forward stagnation point, and the pressure remains approximately constant from about ± 90 to ± 180 degrees (ref 8).

Although the preceding paragraph is actually a description of subsonic wind-tunnel data for two-dimensional flow over circular cylinders, the supersonic wind-tunnel data examined for pressure probes at angles of incidence with the wind stream appear similar. Theoretically and according to the experimental data of ref 6 and 9, the Mach number effects on the radial static pressure distribution of suitably designed probes are insignificant, at least for Mach numbers in the range 1.5 to 3.0. Moreover, the wind-tunnel

* A stagnation point is a point where the flow velocity is zero. In a two-dimensional flow of a perfect incompressible fluid over a circular cylinder two stagnation points occur on the cylindrical surface and are located at the intersections of the cylindrical surface with the flow-velocity vector drawn through the center of the cylinder. The stagnation point located on the windward side is called the forward stagnation point.

**Reynolds number is defined as the product of the model length and wind velocity divided by the undisturbed air kinematic viscosity. The crossflow Reynolds number is based on the crossflow component of the undisturbed wind velocity and the component of model length in the direction of the crossflow velocity.

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data show that the radial static pressure distribution within ± 30 degrees from the forward stagnation point is not influenced by Reynolds number and is in agreement with equation (1). However, the radial static pressure distribution for supersonic flow at locations beyond ± 30 degrees from the forward stagnation point is similar to that noted for two-dimensional incompressible flow over a circular cylinder and is affected by changes of the crossflow Reynolds number (ref 6-9).

Instead of using a single orifice, the instrument error due to an angle of incidence with the wind stream may be substantially reduced by locating two orifices for example at different radial positions and using the average value of the two orifice readings (ref 9). This technique will have application particularly for roll-stabilized missiles, or for missiles where the angle of attack and yaw angles or total angles of incidence are approximately known.

For example the angle of incidence for ground-target missiles at altitudes below 40,000 ft will generally be within 5 degrees. According to the wind-tunnel data of ref 9 where the average value of the static pressures of two orifices was used, the pressure coefficient error* may amount to 0.0025. Thus, at any altitude, the corresponding error in the determination of altitude varies approximately with the square of the vehicle velocity and is less than 42 ft when the vehicle velocity is 1,000 fps. Based on the dynamic pressures for the incident flow given by the preliminary trajectory data for the missile Redstone, cf. table VIII of ref 10 and the ambient pressure-altitude data given by ref 11, the static pressure measurements for altitudes below 40,000 ft will be within 2 percent of the ambient pressure. For this altitude range a 2-percent error in the measurement of the ambient pressure corresponds to a 500-ft error in the determination of the altitude (ref 11).

Of course the accuracy of the fixed-angle probe may be further improved. For example several orifices distributed radially about the probe could be used to measure the ambient pressure. Furthermore, assuming the system of orifices is discriminative, the instantaneous forward stagnation point could be determined as the position having the maximum pressure cf. equation (1). According to equation (1) the true ambient pressure would occur at positions ± 30 degrees from the forward stagnation point.

The above information seems sufficient to indicate the accuracy with which a fixed-angle probe may be expected to measure ambient pressure. Consequently no precise information was sought regarding the much more complicated variation of the radial static pressure distribution for locations beyond ± 30 degrees from the forward stagnation point. Additional wind-tunnel experimental data were not examined.

* The pressure coefficient error as defined in ref 9, is the difference between the measured and true values of the ambient pressure divided by the dynamic pressure for the incident flow.

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As will be discussed in section 6, it is not possible to simulate in a wind tunnel all the flight conditions that may affect the performance of pressure probes. On the other hand, greater accuracy and control in obtaining experimental data are possible in a wind tunnel than in flight. The following flight-test data are included to indicate the accuracy of barometric systems using nose probes and to compare with the wind-tunnel results described above.

Ref 12 discusses the accuracy of a barometric fuzing system for Mach numbers in the range 0.6 to 1.1, where the test vehicles were gasoline fuel tanks having a diameter of 21 in. and a length of 180 in. Six test drops are reported in which the tanks were released from an aircraft at an altitude of approximately 30,000 ft and a speed of 300 mph. In each of the tests, the orifices were radially distributed and located on a probe of special design which was mounted at some distance from the test vehicle so as to reduce the error in the measurement of the atmospheric pressure due to the disturbance of the pressure field by the test vehicle. Rigid nose probes with orifices located 2.0 and 2.5 body diameters forward of the test vehicle resulted in altitude variations of less than 600 ft. The standard deviation in the error in the determination of these measurements is estimated in ref 12 to be 450 ft.

Additional flight tests of a pressure-measuring system using static pressure probes mounted forward of the wing tip and fuselage nose of an aircraft are described in ref 13 for Mach numbers from 0.8 to 1.17. Depending on the Mach number, the orifices were located in the pressure field influenced by the aircraft. This pressure field was theoretically calculated and corrections were applied to determine the true atmospheric pressure. From these results it appears that the atmospheric pressure may be measured with an accuracy to within ± 2 percent of the dynamic pressure* for all altitudes up to at least 50,000 ft. This corresponds to an equivalent altitude error of less than 600 ft.

In concluding the discussion regarding the accuracy of the fixed-angle probe, it is worth noting that the delicate nature of the instrument may seriously affect its use. As previously mentioned, the probe is necessarily slender and shaped like a needle. Production tolerances of the probe, including especially the surface finish, must be held to a minimum. Moreover, for supersonic speeds the probe must be mounted to the missile in a position completely forward of the missile nose shock, since a location in the undisturbed wind stream is essential to obtain accurate measurements of the ambient pressure. For subsonic vehicle speeds, the probe must be placed sufficiently far in front of or along the side of the vehicle so that the orifice pressures are not influenced by the motion of the vehicle. In transportation to the field, in handling, etc, it would be easy to accidentally disturb the alignment of the probe and thereby affect the accuracy of the instrument. Furthermore, due to the location of the probe on the vehicle and the fragility of its over-all design, unless adequate precautions can be taken, the missile vibration, aerodynamic heating, etc occurring in flight may significantly affect the pressure measurements of the probe.

*The dynamic pressure is defined as the product of one half the undisturbed airstream density and the square of the aircraft speed.

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4.2 Free-Swiveling-Vane Nose Probe

The free-swiveling probe is generally of the vane type and consists essentially of a static pressure probe with fins or vanes; it is attached to the missile by means of a swivel joint support. The probe itself has the same needle-like appearance as the fixed angle probe. In the same way that the tail surfaces serve to maintain the alignment of a missile, the vanes and swivel support serve to maintain the self-alignment of the probe with the wind stream. Moreover, it is possible to obtain almost perfect alignment of the probe with the wind stream by using large vane surfaces with the aerodynamic centers of pressure located far aft of the swivel joint. For this reason, the instrument is practically insensitive to changes of the angle of incidence between the missile trajectory and the direction of the wind stream.

Except for the cylindrical part of the probe, the design of the air-flow direction pickup described in ref 14 is the same as that for a free-swiveling vane probe*. Moreover, the self-alignment of the two instruments should be the same. Consequently, since the air-flow direction pickup is more accurate and easier to use for the determination of the instrument alignment with the wind stream, it is preferable to discuss the results obtained with the direction pickup rather than for the pressure probe. The description and results given below are those obtained for the air-flow direction pickup discussed in ref 14.

The over-all exposed length of the air-flow direction pickup is 7 in., the frontal area is approximately 1 in.², and the total weight is 0.32 lb. The instrument was tested in a wind tunnel and in flight at Mach numbers in the range 0.6 to 2.8 and at dynamic pressures of the incident wind up to 65 psi. According to the data, the device is capable of maintaining self-alignment with the wind stream to within 0.2 degrees. Due to lateral accelerations, the angular deviation of the instrument from the wind-stream direction is less than 0.01 degree/g when the dynamic pressure exceeds 2.7 psi. Furthermore, the instrument has withstood shock and static accelerations up to 100 g without damage.

As mentioned, the self-alignment of a free-swiveling-vane pressure probe will be the same as that for the air-flow direction pickup. According to refs 6 and 9, for altitudes below 40,000 ft and dynamic pressures up to at least 65 psi, a pressure probe maintaining an alignment within 0.2 degrees of the wind stream will measure the ambient pressure with an error of less than 1 percent of the true value. The corresponding measurement of the altitude will be in error by less than 300 ft (ref 11).

In conclusion, attention is drawn to the comments made in the final paragraph of the discussion on the fixed-angle probe. These limitations also apply to the free-swiveling-vane probe. Moreover, the free-swiveling-vane

*The air-flow direction pickup is an instrument used to measure the direction of the incident wind.

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probe is even more delicate, since the vanes or the swivel joint may easily be damaged. Because of the free movement of the probe about the swivel joint, the probe is especially vulnerable to the development of air leaks. Furthermore, as is discussed in section 6, the swivel joint may stick in flight because of the expansion of the joint caused by aerodynamic heating. As indicated in the previous discussion, the accuracy of atmospheric pressure measurements for a fixed-angle probe is within 2 percent of the ambient, whereas the accuracy for a free-swiveling-vane probe may be increased to within 1 percent. However, in practice, the improved accuracy obtained by using a free-swiveling probe appears to be more than offset by the added complexity in its design and operation over that of the fixed-angle probe. In addition, the use of the fixed-angle probe has been more common and, because of the small improvement in the accuracy that can be obtained, it is doubtful whether free-swiveling probes will find ordnance application.

4.3 Body-Trailing Probe

As is well known, the velocity fluctuations caused by the motion of a body decrease with increasing distance aft of the body and the return of the pressure in the wake to the ambient value occurs at several body diameters to the rear. Accordingly, it appears possible to measure true atmospheric pressure by extending probes into the body wake. The following description of flight data indicates the accuracy obtainable with the use of such probes.

Assuming that a 1-percent variation in atmospheric pressure is equivalent to an altitude variation of 300 ft, the telemeter data from the free-fall test vehicles of ref 12 indicated that a rigid telescoping trailing probe having orifices 5.7 body diameters aft of the body gave a variation in the pressure measurements equivalent to an altitude variation of 220 ft over the entire Mach number range 0.6 to 1.1. Ref 12 suggests that comparable results are possible using a telescoping probe with a length of about 3 body diameters aft. A flexible body-trailing probe with orifices 5.7 body diameters aft of the body resulted in a pressure variation equivalent to 510 ft over a Mach number range 0.6 to 1.04.

Flight tests using a F86E aircraft were made to investigate methods of determining atmospheric pressure through the transonic speed range in the vicinity of the wake of a jet-propelled aircraft (ref 15). Various trailing probes were extended from the belly of the aircraft at distances varying between 0.65 and 3.98 fuselage diameters behind the jet exhaust. To insure atmospheric pressure measurements with an accuracy within ± 600 ft throughout the Mach number range 0.80 to 1.10, it was necessary to locate the orifices at about 2.5 fuselage diameters behind the aircraft. Orifices can be located closer to the aircraft and yield the same accuracy if the Mach number range is reduced to 0.95 to 1.05. The repeatability of two different pressure pickups for a given flight and for a given instrument during two different flights was within an equivalent altitude variation of ± 250 ft. The maximum deviation in the repeatability for different instruments on different flights corresponded to an equivalent altitude variation of ± 500 ft. All tests were made at altitudes between 40,000 and 20,000 ft, but the results are applicable to any altitude up to at least 50,000 ft.

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The standard deviation in the accuracy of the test data described in refs 12 and 15 is estimated to be 450 ft. From these tests it appears that the velocity fluctuations in the body wake and a return of the pressure in the wake to the undisturbed air-stream value occur at relatively short distances from the body. Accordingly, body-trailing probes may be very useful where high-precision barometric fuzing is required.

4.4 Use of Orifices Located on the Surface Contour of a Vehicle

Sometimes, pressure probes cannot be located at a position where the pressure at the orifices is not influenced by the motion of the vehicle. An example of this situation is a high-speed re-entry missile, where the high rate of aerodynamic heating may structurally deform the probes. Other situations exist which, for example, the extreme vulnerability of the probes to damage, preclude the use of pressure probes. Consequently, orifices are sometimes located on the body contour at a position which will result in the least error in the determination of the atmospheric pressure.

Unfortunately, depending on the vehicle contour itself, the pressure at the orifices is very sensitive to any variation which disturbs the boundary layer at the orifices. This means that the pressure at the orifices will be sensitive to small changes in angle of incidence*, surface roughness and irregularity of the body contour, speed of the vehicle, body surface temperature, aerodynamic heating, etc. The extent to which these parameters affect the orifice pressure depends primarily on the body shape and the location of the orifices. The pressure on the surface of a missile, bomb, or wing will generally be quite different from the undisturbed ambient; this difference may easily amount to one-half the undisturbed value. In addition, large surface pressure gradients may exist which imply that the surface pressure at a given point on the body will rapidly change with small variations in speed, angle of incidence, etc.

Consequently, the problem of using orifices installed in the wall of a vehicle amounts to determining the location for which the variation in the orifice pressure may be most accurately related to the atmospheric pressure and, of course, determining this relation. When the body surface contour is precisely known (that is, the manufacturing tolerances are held within strict limits, such as those for a laboratory model), the relationship between the orifice and atmospheric pressures generally can be established with the required precision of an equivalent altitude variation within ± 600 ft only by experimental data and not by theoretical derivation. Furthermore, as will be explained in section 6, the wind-tunnel simulation of flight conditions cannot be used to determine this relation as it would occur during flight. However, wind-tunnel pressure measurements can be used to aid in determining the proper orifice location by comparing the results with the data from a model of similar shape that has been tested both in a wind-tunnel and in flight. In addition,

*The angle of incidence is defined as the angle formed between the direction of the flight path and the body axis of symmetry.

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the wind-tunnel data may be used to locate the region on the body where the variation in pressure appears to be smallest, and this location will often be a position for which the pressure variation is small in flight.

Rather than enter into a discussion of wind-tunnel tests on bodies which have shapes that are similar to or are used in ordnance devices, the following discussion will be confined to a presentation of flight-test measurements of barometric devices used on some weapons and test research vehicles. Data will be presented for subsonic and supersonic speeds for orifices located on the surface contour including the base of the vehicle.

Ref 16 discusses the results of flight tests of barometric fuzing systems for three current bomb shapes released from an aircraft, where the measurements were made between altitudes of 0 to 10,000 feet above ground and at Mach numbers in the range 0.50 to 0.92. The orifices were located either on the surface contour of the weapon itself or installed in probes lying in a region where the pressure was influenced by the motion of the weapon. Consequently, the determination of the atmospheric pressure was sensitive primarily to Mach number, since the angle of incidence was carefully held to very small values. A total of 185 drop tests are reported and, allowing for an error in the estimate of the Mach number, the standard deviations of the various systems were found to range between 245 and 400 ft.

Additional flight tests to determine the pressure at various locations on research vehicles are reported in refs 17 through 20 for various altitudes at supersonic Mach numbers extending up to 9.89. These data were not obtained for the express purpose of determining atmospheric pressure but rather to evaluate missile performance. Consequently, no precise statements may be made regarding the precision of atmospheric pressure prediction. However, it appears from the close agreement in the pressures obtained between the theoretical and the experimental flight results, from the excellent repeatability of the flight-test data, and from the foregoing discussion, that the conclusions previously obtained concerning the accuracy of a system for measuring atmospheric pressure are applicable for all Mach numbers up to at least 10. Thus, if the pressure probe is suitably designed and the orifices are located in a region where the pressure field is undisturbed by the motion of the vehicle, or the orifices are located where the disturbance of the pressure field is known, the atmospheric pressure may be measured with an accuracy within about 2 percent of the dynamic pressure*.

The location of orifices in the base of the vehicle is of particular interest because of the small possibility of damage occurring to the orifices during launch or flight. This is especially true of long-range ballistic missiles whose high-speed re-entry produces severe aerodynamic heating. At the time of fuzing, the speed of the first generation IRBM and ICBM vehicles will be subsonic with Mach numbers between 0.5 to 0.8, approximately.

*The equivalent altitude variation for a given variation in the dynamic pressure depends approximately only on the square of the vehicle speed, and the altitude variation corresponding to a 2 percent variation in the dynamic pressure for a speed of 1000 fps amounts to between 300 and 400 ft.

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However, because the aerodynamic heating problem of missile re-entry has turned out to be less severe than originally thought, fuzing of the second generation IRBM and ICBM missiles will occur at higher speeds, probably at supersonic speeds below Mach number 3. Fuzing at transonic speeds (Mach numbers between about 0.8 to 1.3) generally will not occur due to the large variations of aerodynamic forces occurring in this speed range for small variations in Mach number. Based on theory and experimental data, the following summary will indicate the accuracy that may be expected using orifices installed in the base of missiles.

The results of measurements in wind tunnels, on firing ranges, and in free-flight tests and the theory show that base pressure values depend on the specific boundary-layer conditions of the body (ref 21 through 25). Consequently, the velocity and temperature profiles in the boundary layer must be known before the atmospheric pressure can be accurately expressed in terms of the base pressure. As is indicated by the experimental data of ref 21, 22, 23 and 25, for body surface temperatures between -50 and +400° F and for Mach numbers up to 5, the base pressure measurement may vary by 10 percent upon changing the surface temperature by 100° F or upon changing the Mach number by 0.2. As might have been expected, the value of the base pressure depends on the body shape. However, the dependence of the base pressure on Mach number has been especially investigated, and it is interesting to note that the above variation with Mach number has been found for a number of bodies of different shapes. Accordingly, when the atmospheric pressure determination depends on the prediction of the vehicle Mach number, in order to limit the error to an equivalent altitude error of less than 1000 ft, the missile velocity must be predicted with an accuracy within 70 fps.

In addition, according to the wind-tunnel results on the 1/6-scale Polaris missile of ref 25, and the 1/2-scale Polaris missile flight test of ref 22, for Mach numbers between 0.7 and 0.9, the base pressure decreases with increasing angle of incidence and the amount of this reduction increases with increasing Mach number. At Mach numbers 0.7, 0.8 and 0.9, the reductions in the base pressure due to a change in the angle of incidence from 0 to 3° are 1, 3 and 5 percent, respectively. The sensitivity of the base pressure to small angles of attack appears to be similar for the 30°-included-angle test model reported in ref 23. According to ref 25, based on existing flight and wind-tunnel data, it is expected that the missile speed at the fuzing altitude can be predicted with an accuracy within ± 30 fps and the standard deviation in determining altitude for the Polaris missile will be 1000 ft, even though the military characteristics permit 1500 ft.

Base pressure measurements on the NACA RM-10 research test vehicle are described in ref 26 at various altitudes for Mach numbers ranging between 0.9 to 3.3. Although the instrumentation did not include an actual fuzing system, the results indicate that the atmospheric pressure may be measured with an accuracy of 3 percent of the dynamic pressure*. Of course,

*See foot-note on page 12, section 4.1.

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because of the location of the orifices in the base of the vehicle, the measurements were sensitive to Mach number and angle of incidence variations. Accordingly, when the Mach number and the angle of incidence are known, the corresponding error in altitude is less than 900 ft.

Since the base pressures are dependent on obtaining the correct boundary layer profiles of velocity, pressure and temperature, the experimental simulation of flight conditions must simulate body surface temperature, Mach number, angle of incidence, aerodynamic heating and Reynolds number. At the fuzing altitude, the Reynolds number and surface roughness of a production-type missile will insure the development of a turbulent boundary layer. Consequently, wind-tunnel and firing-range tests must be performed to simulate these turbulent boundary-layer conditions. For a given Mach number, it appears that the base pressure remains essentially constant with increasing Reynolds number for Reynolds numbers exceeding 4 million. However, aerodynamic heating effects and changes in parameters affecting the boundary layer will also tend to alter the base pressure. Although the dependence of the base pressure on Mach number, angle of incidence, etc is certainly indicated by wind-tunnel and firing-range tests, as will be discussed in section 6, only an actual flight can produce the correct boundary layer and the true base pressure values. However, the above data suggest that the laboratory and free-flight pressure data may often be brought into an agreement within about 10 percent.

4.5 Use of Barometric Devices at High Supersonic and Hypersonic Speeds

For long-range ballistic missiles, the aerodynamic heating may deform the structure supporting the pressure orifices or cause ablation of the structure. Although structural damage due to aerodynamic heating may probably be avoided for IRBM missiles, it is anticipated that ablation and structural deformation will definitely occur for missiles of the ICBM class. The structure and trajectory of the Polaris missile is such that no structural deformation of the vehicle during flight is contemplated (ref 25). Aerodynamic heating is most extreme at the missile nose so that structural deformation and ablation usually originate at the forward part of the body. The damage may spread from the forward to the aft sections of the vehicle. This precludes the use of nose probes and orifices installed in the walls of the vehicle, except possibly in the base. However, the pressures occurring at the rear sections and at the base of the missile are strongly influenced by the upstream flow and body shape so that damage due to aerodynamic heating will generally influence the pressures at the rear of the body.

For all long-range missiles under current consideration and for practically all surface-target missiles, the vehicle speed at fuzing will be less than Mach number 3. Consequently, the problem of determining atmospheric pressure for long-range missiles by means of a pressure-sensing system is similar to that previously discussed with the exception that the body structure may have undergone some deformation during flight and the missile speed will generally not be as well known. However, it appears that for IRBM and ICBM vehicles, the only practical way of sensing atmospheric pressure is by means of body-trailing probes with orifices in the wake far enough downstream so that the pressure becomes approximately equal to the undisturbed airstream

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21

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value (section 4.3) or by installing orifices in the missile base. The use of body-trailing probes is understandably a much more difficult engineering problem than use of base pressure probes. However, as was discussed in section 4.4, the accuracy of base pressure measurements will be in doubt insofar as they are sensitive to changes occurring in the boundary layer of the missile. Accordingly, errors in the determination of atmospheric pressure by means of base pressures will result due to changes in the body shape, errors in the estimation of the Mach number, body surface temperature, etc at the fuzing altitude.

Some wind-tunnel and flight tests have been made to predict the ablation and structural deformation of missile shapes in flight. It is conceivable that such tests will lead to resolving some of the uncertainty in the accuracy of base pressure measurements to determine altitude for ICBM vehicles.

5. THE BARO-SWITCH ELEMENT

The behavior and detailed testing procedures of a number of barometric switch elements are reported in ref 27, 28, and 29. These elements are intended for use in arming and fuzing devices for altitudes up to 100,000 ft. Of course, the design of a switch depends on the conditions under which it is to operate. Although the altitude and the operational use will affect the design of the instrument, the parameters which affect performance will be essentially similar for all switches. Accordingly, the description of the parameters that affect performance will be limited to a single switch, that of the MC-5 instrument of the Sandia Corporation. The experimental results indicate that a baro-switch can be designed with high precision for practically any condition of altitude and missile speed and contributes one of the smallest errors in the determination of altitude.

Primarily, the operation of a baro-switch is sensitive to temperature, pressure and mechanical vibration. In addition, errors in the instrument may result because of variations in the pressure, instrumental repeatability, pressure rate sensitivity, remote-setting of the mechanism, and due to storage. According to ref 27, it is probable that baro-switches can be made insensitive to temperature and the operational standard deviation will then be reduced to 100 ft or less.

As described in ref 27, the MC-5 remote-setting baro-switch assembly consists of four mechanically ganged aneroid-diaphragm assemblies, each containing its own seal-in switch contact. The four diaphragm assemblies are mounted in a single case of approximately 12 x 14 x 3 in. and weigh approximately 14 1/2 lb. A 26-volt 400-cps a-c positioning motor provides for changing of altitude settings of the firing point until the time the weapon is released. Each of the aneroid-diaphragm assemblies is evacuated to a pressure of approximately 20 mm of Hg and the entire MC-5 case is pressure-sealed to minimize leakage.

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The results of the tests on the MC-5 baro-switch to determine the sensitivity of the operation of the device to the above parameters are given in ref 27. The switches were tested at ambient temperatures of 0, 77 and 120°F and pressure-altitude settings corresponding to sea level, 2000, 5000, 10,000 and 14,000 ft. In addition, a few tests were conducted at -90°F to determine the low-temperature operability.

Defining the pressure sensitivity as the minimum change in pressure that will cause the switch contacts to open if they are closed or to close if they are open, for altitudes between sea level and 10,000 ft and in the absence of all other effects, it is claimed that the MC-5 switch will operate at any specified temperature with a standard deviation of less than about 50 ft.

When no correction is made for the baro-switch temperature, the operational standard deviation is approximately 70 ft for the altitudes from sea level to 10,000 ft; the standard deviation increases to 100 ft when the altitude range is increased from sea level to 18,000 ft.

The standard deviation of the repeatability of the MC-5 baro-switch under a given condition is approximately 10 ft for pressure altitudes in the range sea level to 18,000 ft and temperatures between 0 and 120°F.

Pressure-rate sensitivity signifies the variation in the switch operation under various rates of change of pressure. Pressure-rate sensitivity is a measure of the dynamic response in contrast to the static parameters discussed above. To determine the effect of this parameter on the switch operation, diving tests simulating the changes in pressure occurring in flight are carried out in environmental chambers. The standard deviation in the error due to pressure-rate sensitivity for a barometric switch is estimated in ref 27 to be about 50 ft, which is in agreement with the experimental tests described in ref 28.

No variation in the operation of the switch is expected because of storage, but the standard deviation in the error due to the remote setting of the switch is estimated to be about 50 ft.

The effect of mechanical vibration on the switch contacts and diaphragm assemblies is to cause early closure of the contacts and thereby cause early functioning. The MC-5 switch is therefore mounted on a support which isolates it from vibrations to which it is sensitive. The standard deviation in the operation of the MC-5 baro-switch due to mechanical vibration effects is estimated to be about 50 ft.

Forming the rms of the above standard deviations, the over-all standard deviation for the MC-5 switch is 110 ft.

The reliability of the MC-5 baro-switch is based on experimental test results (including drop-test data) and from receiving inspection test data. Accordingly, the dud probability is estimated to be 1/5000 and the probability of a premature operation is estimated as 1/10,000.

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6. WIND-TUNNEL AND LABORATORY SIMULATION OF FLIGHT CONDITIONS

It was noted in the preceding sections that the laboratory simulation of flight conditions generally precedes the flight-test evaluation of barometric devices. The value of wind-tunnel tests is primarily to aid in determining the location of the pressure orifices on the body contour or in designing the pressure probes so that the orifice pressure will be uniquely related to the undisturbed ambient. In addition, the wind-tunnel results will give an approximate relation between the pressures at the orifice and the undisturbed airstream. The application of this relation to flight conditions is based on the large amount of wind-tunnel and flight-test data that have been previously correlated for bodies of similar aerodynamic shape.

However, the wind tunnel can only simulate steady-state conditions so that the performance of a barometric device under the dynamic conditions occurring in flight and the sensitivity of the baro-switch to such factors as the rate of change of atmospheric pressure and mechanical vibration cannot be evaluated. Accordingly, environmental chambers in which the temperature and pressure can be rapidly changed and the instrument mechanically vibrated are used to evaluate the dynamic response of the system. Thus, the laboratory evaluation of a barometric device consists of two parts: (1) the wind-tunnel tests; and (2) the environmental chamber tests, which are used to determine the dynamic response of the baro-switch when the instrument is subjected to the environmental conditions that are expected to occur in flight. The following discussion will indicate the validity of the laboratory simulation of flight conditions in evaluating the performance of a barometric device.

The wind-tunnel simulation of flight conditions is predicated on the simulation of the two nondimensional parameters, Reynolds number and Mach number. Simultaneous simulation of the flight Mach number and crossflow Reynolds number on a nose-type probe is possible in a wind tunnel by varying the angle of incidence of the probe. The effects of Mach number are small or insignificant for probes and consequently the wind-tunnel simulation can be simplified by simulating the crossflow Reynolds number through the entire range at merely two or three different Mach numbers representative of the Mach-number range.

This procedure is not possible for orifices located on the vehicle itself. Although the crossflow Reynolds number and Mach number primarily govern the radial pressure distribution for nose-type probes, the effects of aerodynamic heating, surface temperatures, surface roughness and other parameters that influence the boundary layer will alter the pressure distribution on the body. The effect of these additional boundary-layer parameters on the pressure distribution depends on the body itself and the position on the body which is being observed. The boundary-layer parameters are not generally simulated because it is not possible to simultaneously simulate actual ambient density, temperature, and pressure as well as the actual missile speed occurring in flight. This is due to the fact that the stagnation conditions of the air for the usual supersonic tunnel will be approximately equal to the sea-level atmospheric conditions*. For example, the simulation of sea-level ambient

*That is, when the air has zero velocity, the wind-tunnel density, temperature and pressure are the same as that of the surrounding atmosphere.

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density at Mach numbers 2, 3 and 4 would require a variable-density supersonic wind tunnel with stagnation densities of 4.4, 13.2 and 36 atmospheres, respectively. The simulation of an ambient temperature of 60°F at Mach numbers 2, 3 and 4 would require stagnation temperatures of 475, 1000 and 1,720°F, respectively.

There are, however, a limited number of variable atmospheric wind tunnels which extend the simulation of atmospheric conditions to a range of altitudes as well as simultaneous simulation of the crossflow Reynolds number and Mach number. The small number of variable atmospheric tunnels available generally makes it necessary to test in the nonvariable atmospheric wind-tunnel facilities. Accordingly, the evaluation of static pressure probes and body orifice locations are obtained from experimental tunnel data with sea-level atmospheric stagnation conditions. Some indication of the difference between the wind-tunnel and flight values of the density, temperature and pressure may be seen as follows. Consider, for example, a stagnation density of 0.00238 slug/ft³ (the value at sea level) and a stagnation temperature of 100°F. At Mach numbers 2 and 3 the static density and temperature in the wind tunnel would be about 0.000547 and 0.000181 slug/ft³ and -149 and -260°F, respectively. The above densities occur during flight at altitudes of about 41,000 and 64,000 ft, respectively, whereas for altitudes up to 75 miles the minimum ambient temperature is only about 70°F. The corresponding wind-tunnel static pressures for Mach numbers 2 and 3 are 1.70 and 0.431 psi, and would occur at altitudes of about 50,000 and 79,000 ft. Moreover, for the above stagnation conditions, the tunnel wind speeds at Mach numbers 2 and 3 would be only 1730 and 2080 fps. Even at Mach number infinity, because of the temperature reduction, the tunnel wind speed would be only 2600 fps.

The preceding example shows that much smaller values of the density, temperature, pressure and wind speed are obtained in a wind tunnel than those occurring in flight. This affects the application of wind-tunnel data to flight conditions. As was noted in section 4, for nose pressure probes, the difference between the true and measured values of the ambient pressure may be expressed by the product of the pressure coefficient error and the dynamic pressure of the incident wind. For nose probes, the pressure coefficient error was noted to be essentially a function of the crossflow Reynolds number and may be simulated in the wind tunnel at various Mach numbers. However, due to the reduced values of the density and wind speed, the tunnel dynamic pressure of the incident wind will be less than that occurring in flight. For example, the dynamic pressure for an altitude of 10,000 ft and at Mach numbers 2 and 3 amounts to 28.2 and 63.2 psi, whereas the wind tunnel dynamic pressures based on sea-level atmospheric stagnation conditions are only 5.70 and 2.72 psi, respectively. As a matter of fact, the dynamic pressure for flight at any altitude increases as the square of the Mach number, whereas the dynamic pressure in the wind tunnel attains a maximum value at Mach number $\sqrt{2}$ and then decreases asymptotically toward zero with increasing Mach number. Hence, for the same pressure coefficient error, the difference between the measured and true pressures occurring in flight is larger than that occurring in the wind tunnel by the value of the ratio of their respective dynamic pressures. For the above example, at Mach numbers 2 and 3 the differences occurring in flight are larger than for the wind tunnel by factors of 4.95 and 23.2, respectively.

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As was previously noted, based on stagnation conditions, the wind-tunnel static pressures at Mach numbers 2 and 3 are 1.70 and 0.431 psi. At an altitude of 10,000 ft, the ambient pressure is 10.1 psi. Since the crossflow Reynolds number for the wind-tunnel and flight conditions may be assumed equal, the pressure coefficient error of a nose probe may also be assumed to be the same; its value will be denoted by 0.016. Then, for Mach numbers 2 and 3, the percent static pressure errors measured in the wind tunnel would be 3.366 and 6.306, and the percent ambient pressure errors in flight would be 2.796 and 6.266. Thus, for the same pressure coefficient error, the percent static pressure errors obtained in the wind tunnel will be comparable to the percent ambient pressure errors obtained in flight. The comparisons will also be similar for other altitudes and Mach numbers.

The steady-state temperature of the probe in a wind tunnel will have a value slightly less than the stagnation temperature; therefore, it will have a value slightly less than the sea-level atmospheric temperature. The atmospheric temperatures will be much lower than the steady-state body temperatures occurring in flight. For example, for an altitude of 10,000 ft at Mach numbers 2, 3 and 4, the steady-state flight temperatures of the probe would be 370, 805 and 1415°F, respectively. Since the heat capacity of the probe is small, the probe will rapidly approach steady-state values, especially at low altitudes where the aerodynamic heating is highest. Thus, the wind-tunnel surface temperatures of the probe or vehicle will be much lower than those occurring in flight. Precautions must be taken in the design and calibration of the probe or in the determination of the body orifice location so that the pressure-gage reading will not be affected by temperature variations. In particular, special precaution must be taken for the free-swiveling-type probe so that the expansion due to aerodynamic heating will not cause the swivel joint to stick.

As indicated earlier, the performance of the baro-switch itself may be evaluated in the laboratory by means of environmental chambers. An environmental chamber is essentially a chamber in which the baro-switch can be mechanically vibrated while simultaneously subjected to varying temperatures and pressures. Assuming the trajectory of the vehicle and the approximate relation between the orifice and atmospheric pressures are known, the pressure and temperature within the chamber is varied as a function of time to simulate the conditions that the baro-switch would encounter during flight. As is clear, this procedure evaluates only the dynamic response of the baro-switch and errors in the dynamic response of the instrument are in addition to those occurring in the relation between the orifice and atmospheric pressures.

The environmental chamber is used to perform dive tests, which are provided to simulate the flight conditions that would be experienced by a baro-switch on a descending vehicle such as a surface-target weapon (ref 30, 31). The dive tests attempt to determine the accuracy of the baro-switch by setting the instrument to fire at a preset altitude and evaluate the performance of the instrument on the basis of the difference between the preset and dive pressures. This pressure difference is expressed in terms of equivalent altitude error, as determined from the standard variation of pressure with altitude.

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The baro-switch may be made insensitive to the mechanical vibrations occurring in flight by designing the instrument support system to transmit only those frequencies which have little effect on the switch response. The design of such a support system can be accomplished by laboratory testing of mechanical vibration without direct reference to the actual vibrations occurring in flight.

In addition, tests are performed to insure the repeatability of closure of the switch to simulate storage conditions. Thus, various tests are performed in which the temperatures and pressures are cyclically varied between about -65 to 165°F and between about ± 20 percent of sea-level atmospheric pressure. Additional studies are performed in the laboratory to insure a unique response of the diaphragm in terms of load versus deflection. Air leakage into the cell may affect the load-versus-deflection response of the diaphragm as well as alter the breakdown voltage at which the switch opens or closes.

The above and other laboratory tests evaluate the instrument prior to testing in flight. Thus, the design of a baro-switch is intimately associated with the performance of a number of laboratory tests and checkout procedures. The laboratory tests of a baro-switch are extensive and a close correlation exists with flight performance.

On the basis of the foregoing discussion, it appears that when pressure probes are used and are located away from the pressure disturbance caused by the moving vehicle, the probes will permit an accurate measure of the atmospheric pressure. Such probes have been evaluated for all speeds up to at least Mach number 5 and are applicable for use on practically any weapon. New designs of pressure probes may be evolved from those already proved and by additional wind-tunnel tests. When the orifices must be located in a region where the pressures are altered by the moving vehicle, such as on the body contour itself, wind-tunnel tests will help in determining a proper location for the orifices and suggest an approximate relation between the orifice and undisturbed free-stream pressures. The laboratory evaluation of the baro-switch appears to agree closely with flight test results.

7. METEOROLOGIC EFFECTS ON ALTITUDE DETERMINATION

The pressure setting of a barometric device will depend largely on its use. A discussion of the military characteristics of the various barometric devices would be very complex and involved. However, it appears that the basis of pressure predictions will generally be limited in practice to the following circumstances: (1) for a given geographical area, the barometric device will be set at the average monthly or seasonal value of the atmospheric pressure corresponding to the required altitude, and/or (2) on a given day or for several days prior to the use of the barometric device, pressure data will be available at one or more stations at ground level and possibly as a function of altitude for altitudes extending up to 75,000 ft.

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27

SECRET

Based on this information, it is required to predict the pressure at a given altitude over a target for which the pressures are not known. As will be shown below, the equivalent altitude error in the prediction of the atmospheric pressure is generally smaller than the errors in the barometric device itself.

Radiosonde weather data recorded by means of balloons is internationally made available twice daily for altitudes up to 75,000 ft. In general, the average atmospheric pressure at a given altitude depends primarily on the time of year and latitude. Figures 1 and 2 (photographic copies of Figures 18 and 19 of ref 32) show the annual average standard deviations of interdiurnal pressure* and the daily pressure variations in North America as functions of altitude and latitude. As may be seen from these data, the standard deviations of the two figures are approximately the same and in each case the pressure variations increase with increasing distance from the equator. In order to express the variation of pressure in terms of altitude, a 1-percent variation of pressure is equivalent to an altitude variation of 200 ft at an altitude of 35,000 ft and increases linearly to about 300 ft at sea level.

According to ref 33, based on the studies and targets selected by the Air Weather Service and the Global Weather Control of SAC, the largest standard deviation occurs in January and is about 450 ft for 5 percent of the targets and is less than 335 ft for 75 percent of the targets. Twelve-hour, twenty-four hour and interdiurnal forecasts of changes in weather maps by experienced climatologists indicate that the standard deviations in the pressure during January correspond to altitude variations of 150, 225 and 350 ft, respectively. The standard deviations for all other times of the year were noted to correspond to between one-half to the full amount of the altitude variations given above, the deviations generally increasing from the minimum values in July to the maximum values in January. Thus, the standard deviation of the error in the pressure prediction will be about 1 percent of the atmospheric pressure, and accordingly will generally be smaller than the error in the instrumental pressure determination (section 4).

It is interesting to note that a correlation exists between atmospheric temperatures and pressures, particularly in the altitude interval from 6,000 to 30,000 ft (ref 34). For these altitudes, consideration of atmospheric temperatures will tend to increase the accuracy to which pressure predictions may be made.

8. SUMMARY

The problems involved in the design and the parameters affecting the performance of a barometric device have been described. In addition, specific barometric systems have been described for subsonic and supersonic speeds, for altitudes up to 100,000 ft. The errors in the measurement of atmospheric pressure consist essentially of those due to the baro-switch

* An interdiurnal variation is defined as the rms difference between the pressures at the beginning and end of a 24-hr period. Accordingly, an interdiurnal forecast is a prediction that the present pressure will last 24 hr in the future.

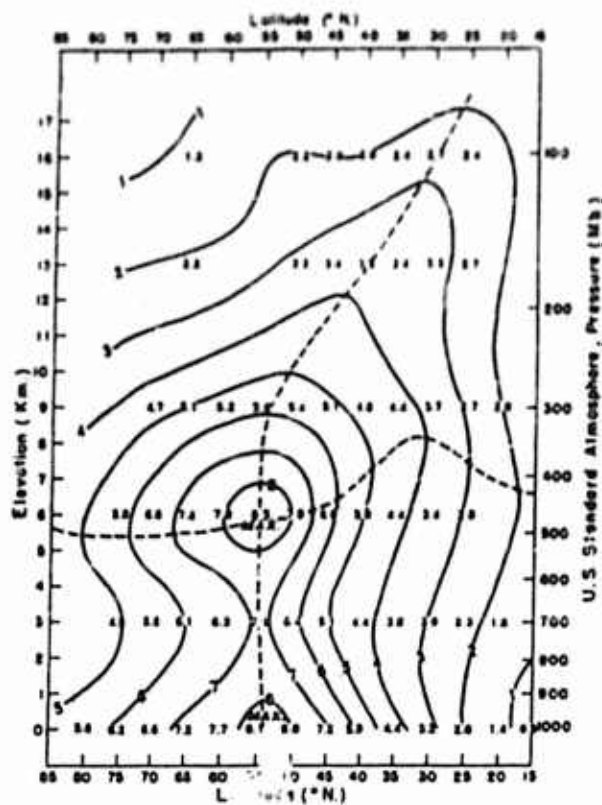


FIG. 1 Atmospheric cross section giving annual average standard deviation of interdiurnal pressure change in North America in relation to latitude and elevation. Solid curves indicate equal interdiurnal change in millibars. Dashed curves are axes of maximum interdiurnal change, considered with respect to latitude or elevation.

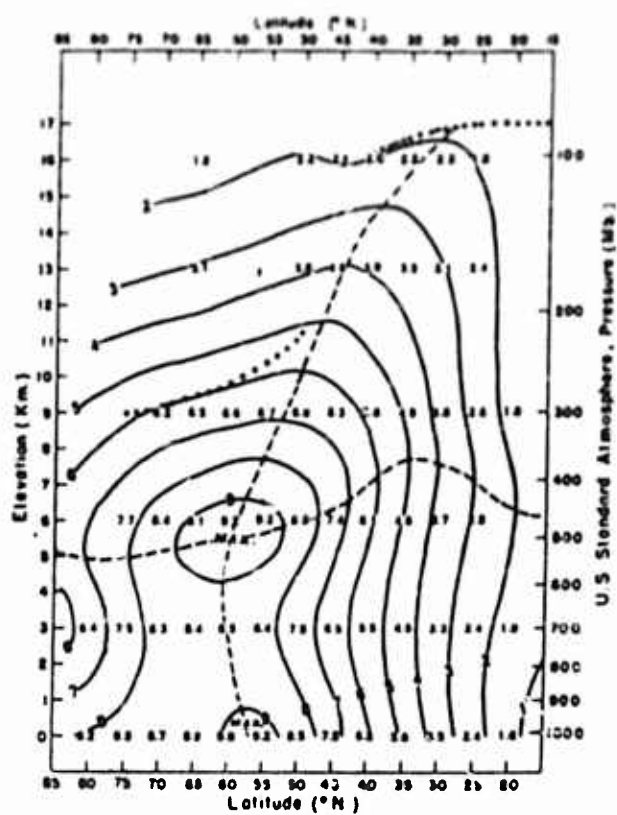


FIG. 2 Atmospheric cross section giving annual average standard deviation of daily pressure in North America in relation to latitude and elevation. Solid curves indicate equal standard deviation in millibars. Dashed curves are axes of maximum standard deviation, considered with respect to latitude or elevation.

(Source: 'Ref 32)

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and in the relation between the orifice and undisturbed atmospheric pressures. The operational standard deviation of flight-tested baro-switches are approximately 100 ft. It was seen that the accuracy of measuring atmospheric pressure was very largely a function of the location of the orifices with respect to the moving vehicle. Accordingly, the standard deviation in the error relating the orifice pressure to the undisturbed ambient pressure may be as small as 200 ft or larger than 3000 ft.

The error in the altitude determination consists of the errors in the measurement of atmospheric pressure in addition to the error in the pressure-altitude prediction. The maximum standard deviation in the pressure-altitude prediction occurs for the month of January and will have a value between approximately 300 and 400 ft; the standard deviation gradually decreases to a minimum equal to about half this value for July. Generally, the error in the altitude determination by barometric devices occurs primarily in the relation between the orifice and undisturbed atmospheric pressures.

30
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